Material Condition and Usage Monitoring Sensors and Algorithms for Adaptive Management of Legacy and New Platforms

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Abstract

Adaptive asset management requires not only real time usage state monitoring and fault-to-failure detection/monitoring, but also observability of material condition variations for a statistically sufficient population of components. Until recently this was not practical. Now new sensor technologies, such as JENTEK's embeddable and scanning MWM-Arrays, offer capability to monitor prefault (e.g., precrack) damage accumulation. JENTEK's technology offers both unique capability for reducing costs of inspecting and maintaining legacy platforms, and new potential to support material and component design decisions for new platforms to promote improved damage accumulation observability. One goal might be to increase the likelihood of graceful (e.g., gradual) damage accumulation/failure modes that can be detected within sufficient time to avoid catastrophic failures, limit repair costs and support condition-based and even preventive maintenance.

JENTEK has programs with the Air Force, Navy, Army, NASA, DOE, FAA and OEMs directly relating to CBM and PHM for critical assets. JENTEK has developed a unique capability for rapid prototyping and transitioning of solutions to the depot/field. JENTEK has unique sensor and system technologies for damage, usage state, and material condition monitoring. This includes not only fault detection and monitoring, but also mapping of residual stresses and prefault damage accumulation. JENTEK products also include analytical software tools for estimation of multiple unknown properties and failure/condition assessment to support field/depot CBM and PHM decisions, as well as future concepts for adaptive asset management including prognostics.

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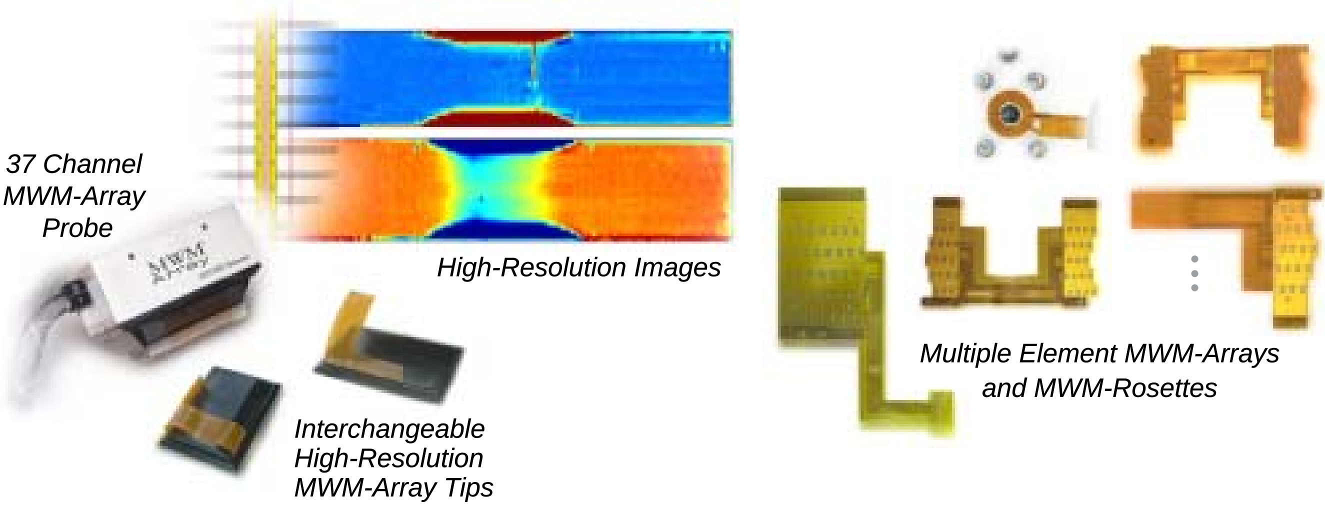

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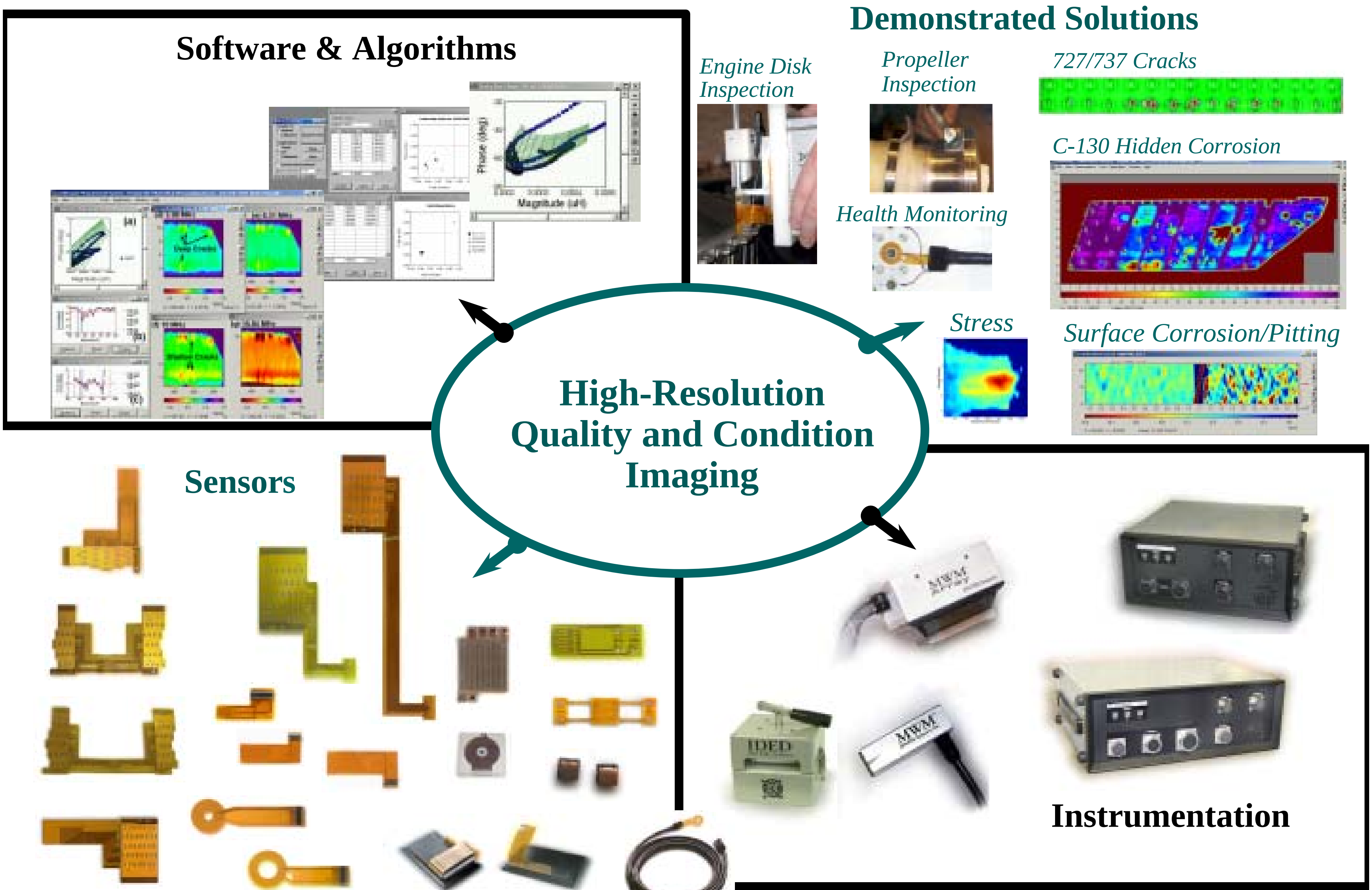
JENTEK's Evolutionary Product Line



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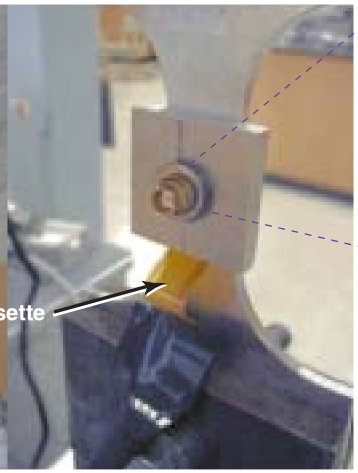
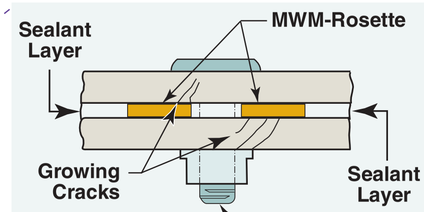
SURFACE-MOUNTED SENSORS:
FATIGUE TESTING & ON-AIRCRAFT MONITORING

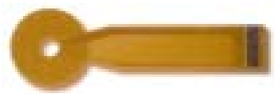
MWM-Rosette mounted around a steel fastener



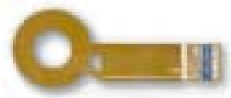
MWM-Rosette mounted between two aluminum alloy layers



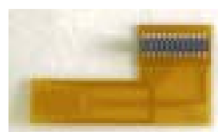
Detail



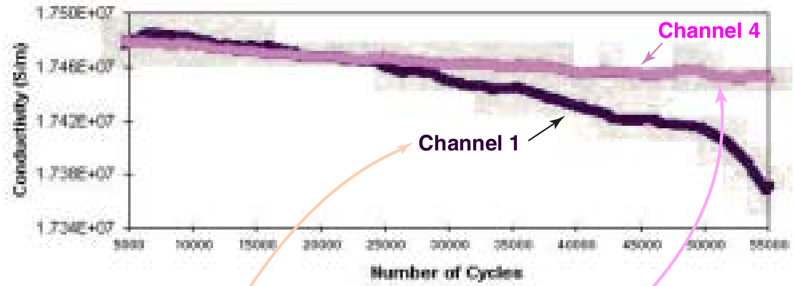
7-Channel MWM-Rosette



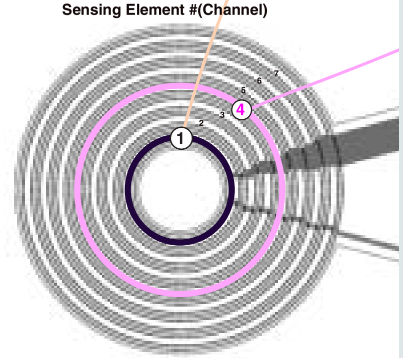
4-Channel MWM-Rosette

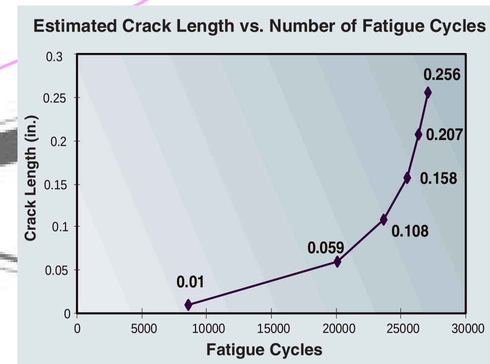


Linear MWM-Array

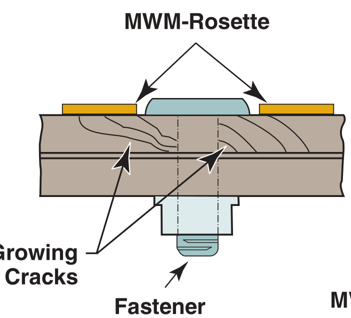


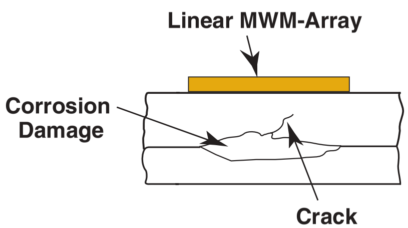
Data from a fatigue test with an MWM-Rosette mounted around a fastener in an aluminum dogbone specimen and between layers of aluminum. A 0.6-mm (0.024-in) long crack was detected by Channel 1 of the MWM-Rosette embedded between the layers. The innermost Channel 1 is close to the fastener hole; Channel 4 is farther away from the fastener.

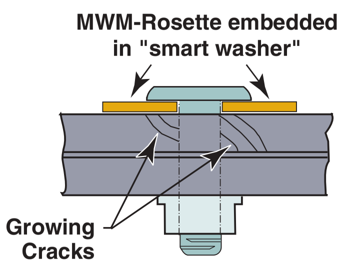




Surface Mounted MWM-Array Configurations







MWM-Rosette on P-3 Orion Fatigue Test

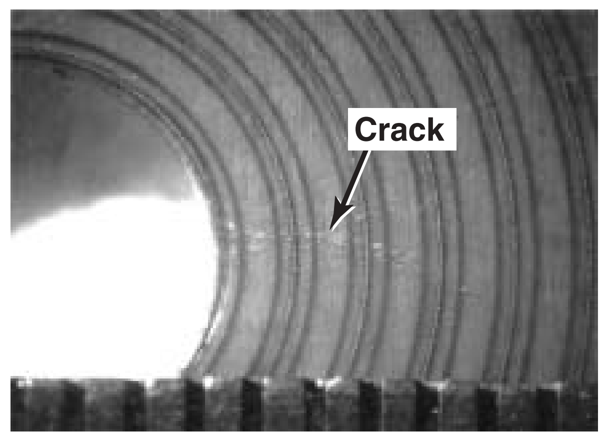
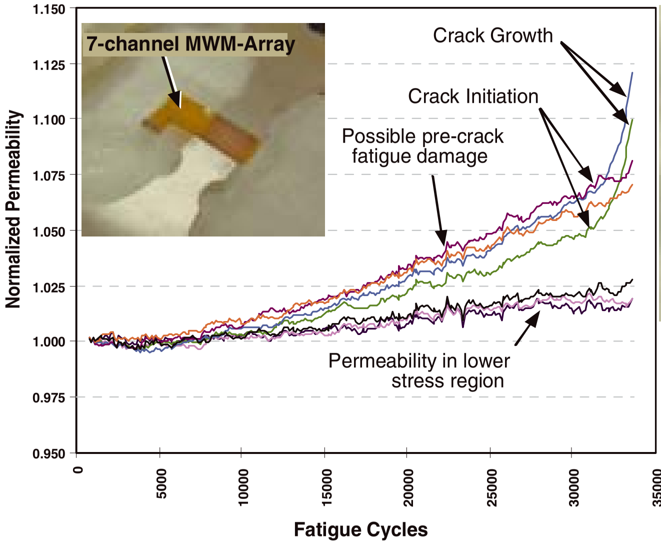


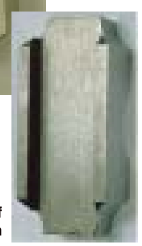
Image of MWM-Rosette used for Fatigue Crack Growth Monitoring

IN-SITU FATIGUE & STRESS MONITORING FOR HIGH STRENGTH STEEL LANDING GEAR

Fatigue Damage in 4340 Steel



Shot peened 4340 specimen



Back of specimen

Fatigue damage zone

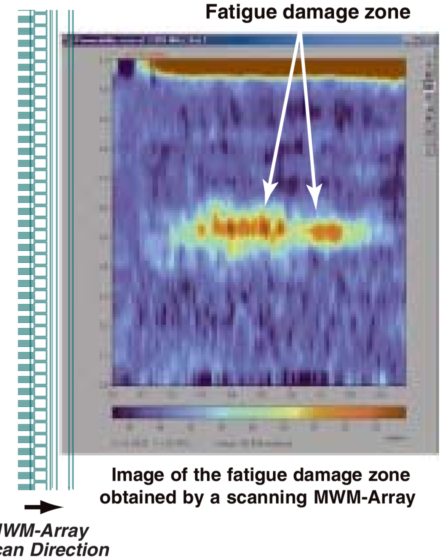
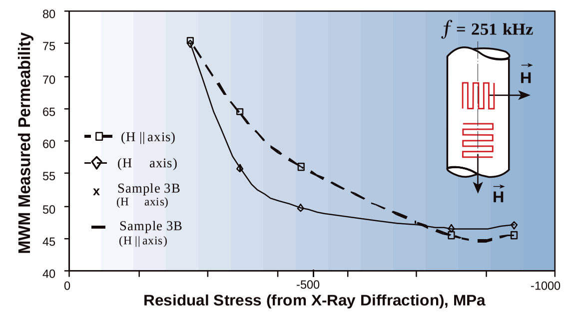


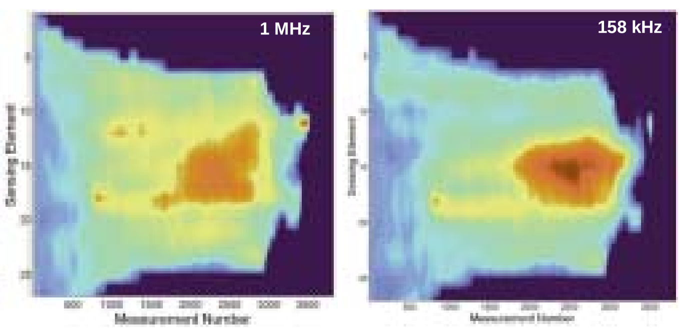
Image of the fatigue damage zone obtained by a scanning MWM-Array

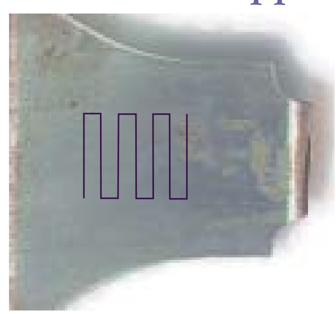
Grind Repair Assessment



Landing Gear Component

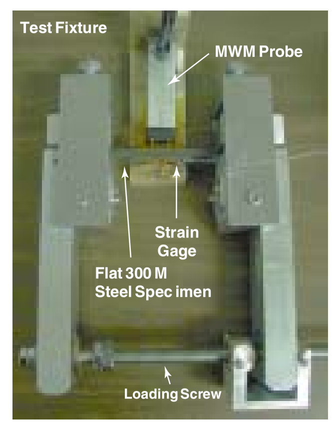
Residual and Applied Stress Estimation



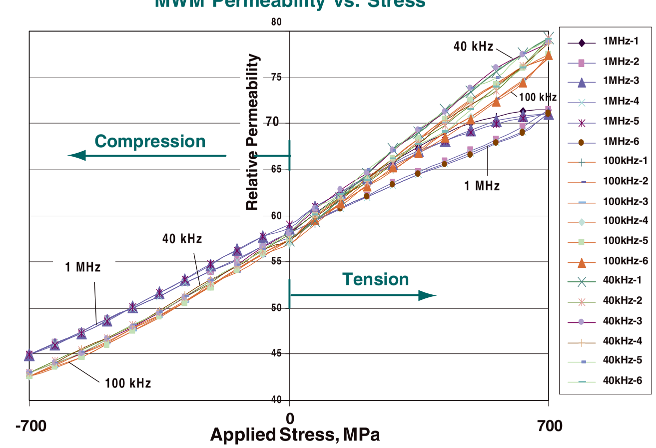


MWM-Array oriented perpendicular to the loading axis

MWM-Array generated normalized permeability images for a double-notched, low-alloy 4340 steel tensile specimen loaded to failure. Images produced after failure. The images illustrate the ability to obtain distribution of residual stresses due to correlation between permeability and stresses.

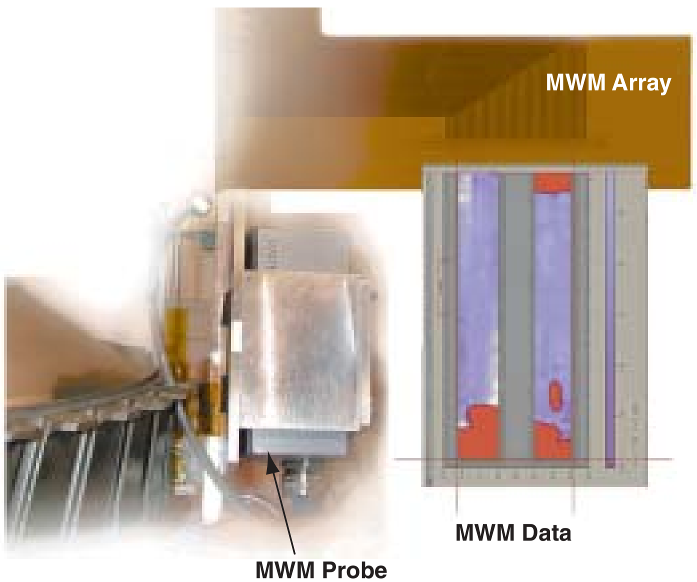


MWM Permeability vs. Stress

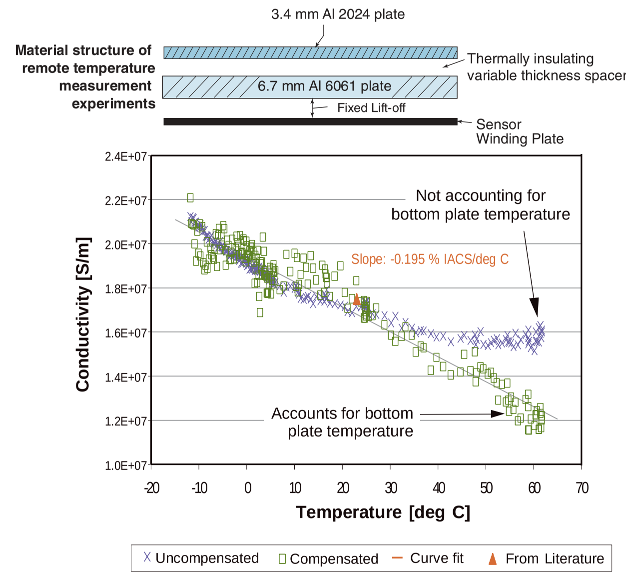


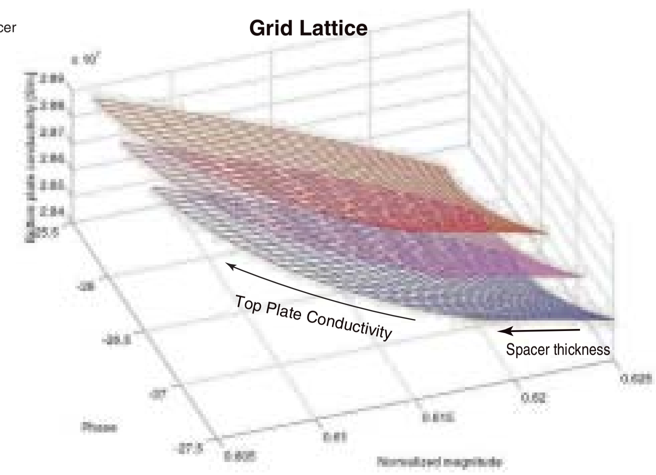
ENGINE CBM AND PHM

Engine Disk Inspection

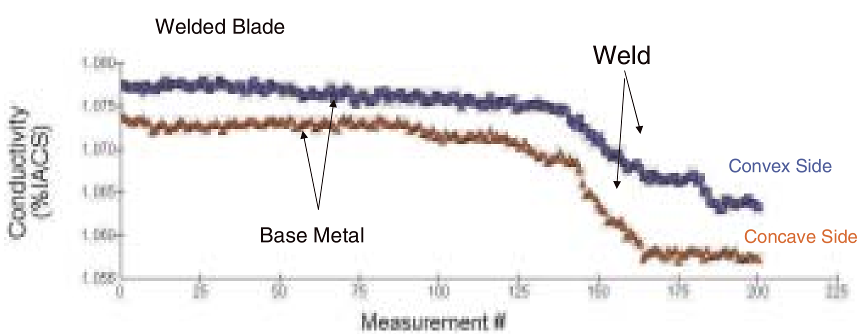


Remote, Through-Wall Temperature Measurement

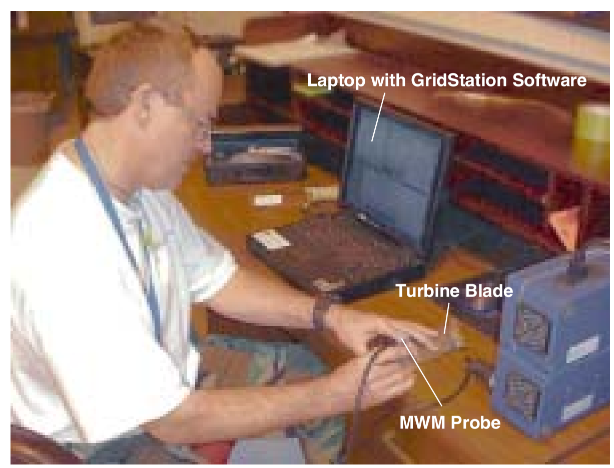


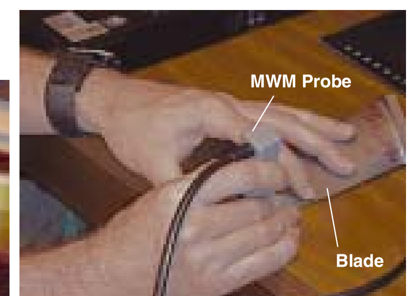


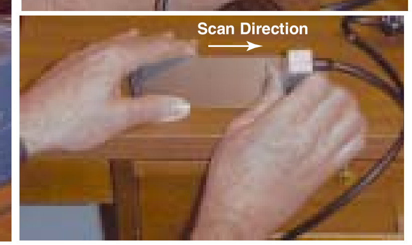
Example: Identification of Weld Repaired F402 Engine Blades



- Effective, rapid procedure
- Blades with weld repairs readily identified

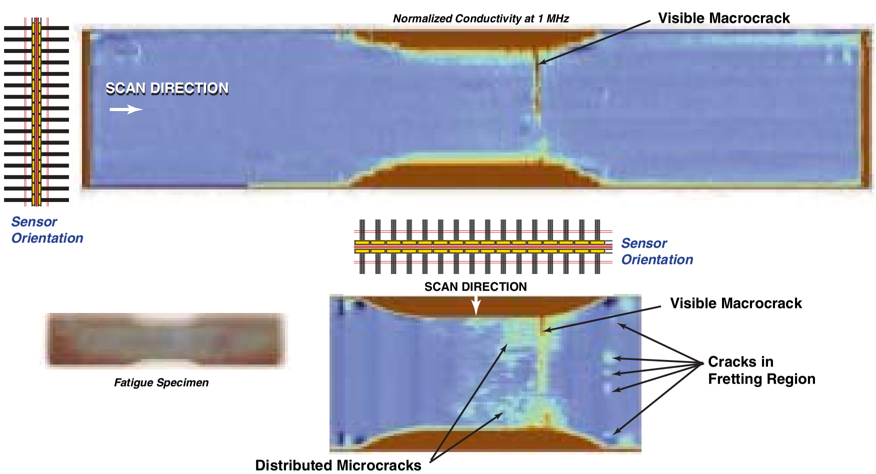




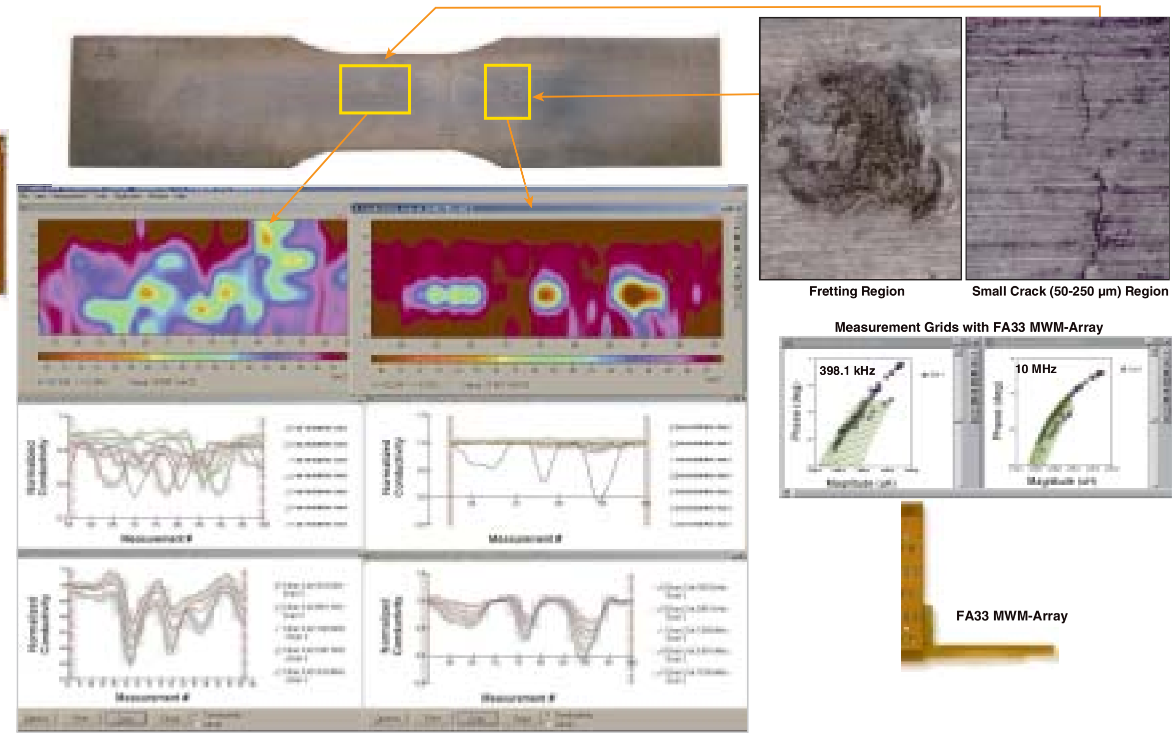


SURFACE DAMAGE CHARACTERIZATION

Distributed Microcracks and Macrocracks from Bending Fatigue



Next generation MWM-Arrays for Fatigue Damage

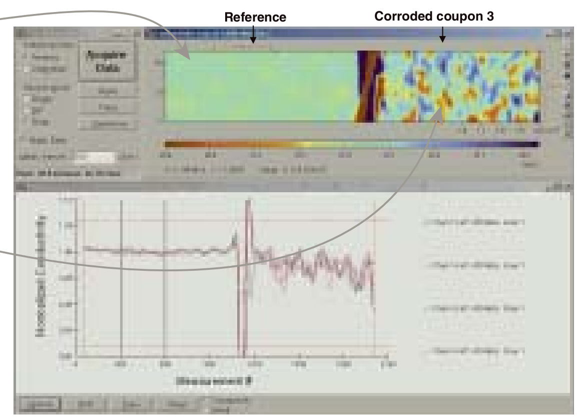


Corrosion Damage Imaging

U.S. Army Corrosion Retardant Testing Coupons

Coupons Supplied by US Army

- Corrosion coupons removed after a 1-year exposure from a seaside corrosion test
  - For each material, selected coupons scanned by imaging MWM-Array



Images of reference Al 7075-T6 coupon (left) and the more severely corroded Al 7075-T6 coupon (right) obtained at 1 MHz

Corrosion Detection without Paint Removal

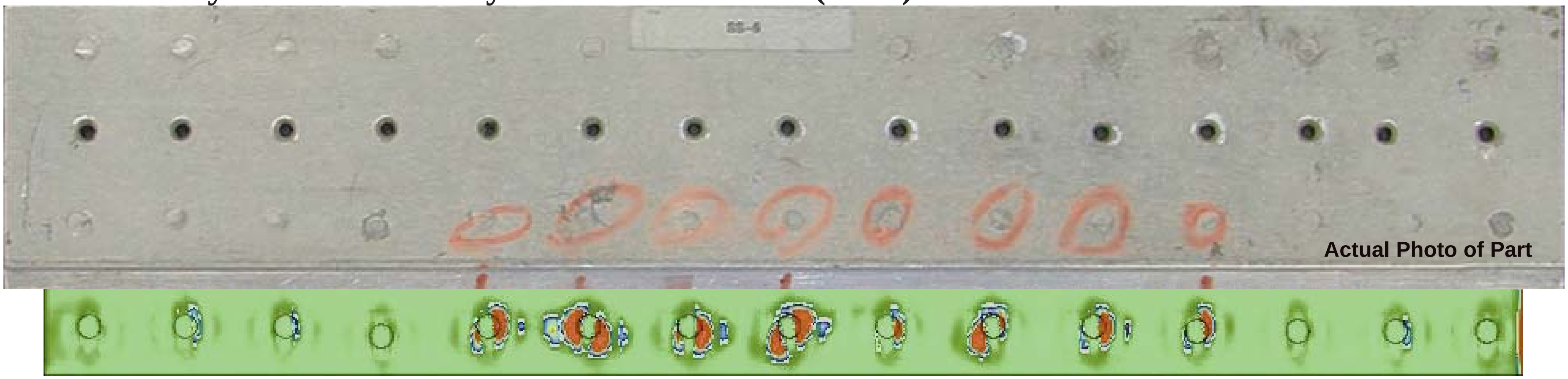
- MWM images reveal pitting and intergranular corrosion/exfoliation
- MWM images can be used to identify corrosion mechanism and characterize severity of corrosion
- MWM data can be used to prioritize corroded sites for maintenance or corrective actions

Note: 0.004 in. insulating shim used to simulate paint layer
Scan width 12 mm, scan length 100 mm

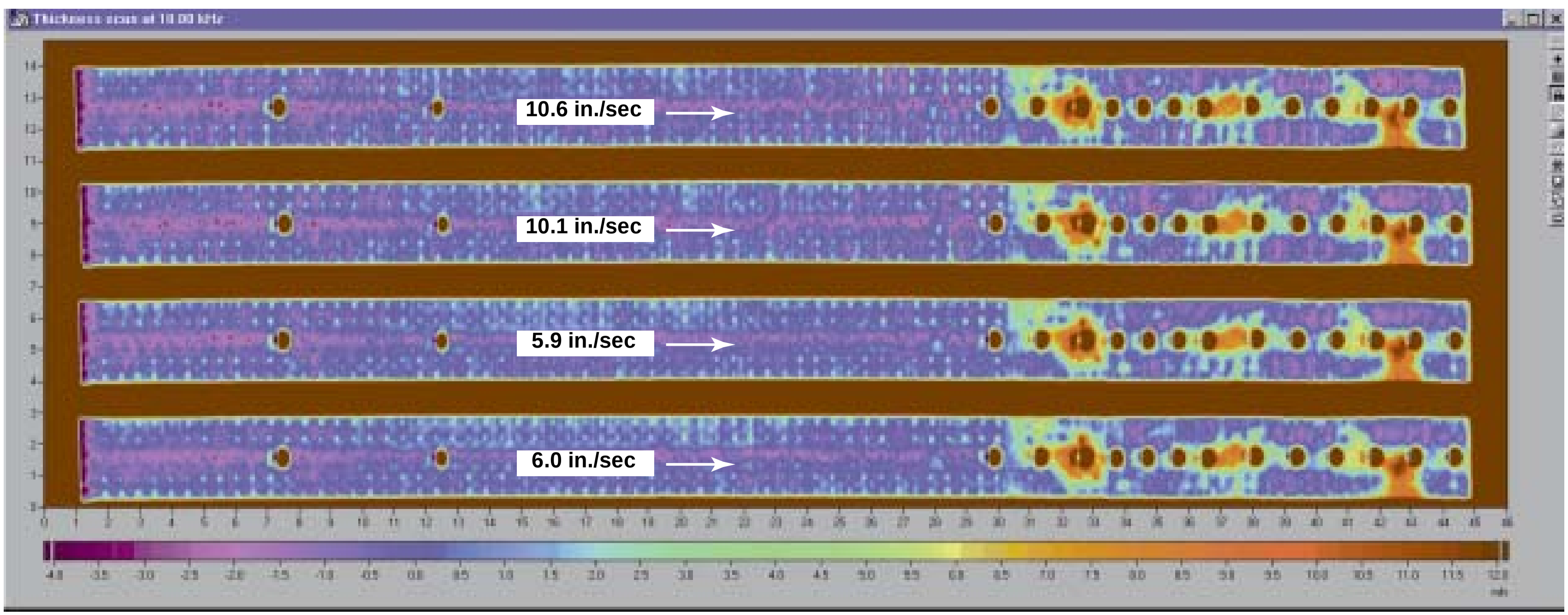
HIDDEN DAMAGE IMAGING

Competitive Advantages: Increased Sensitivity and Speed

MWM-Array: 727/737 3rd Layer Crack Detection (FAA)

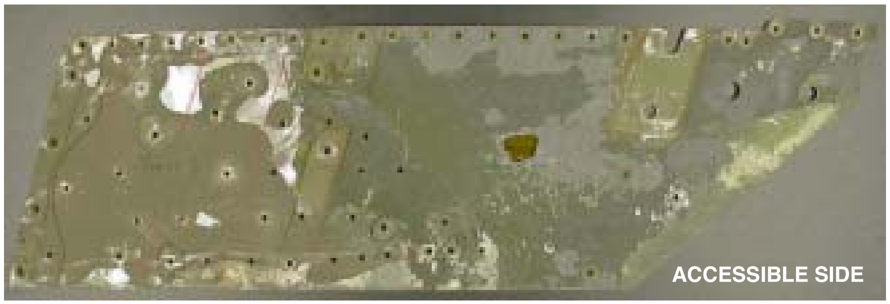


MWM-Array: KC135 Lap Joint Hidden Corrosion (AF, Navy)

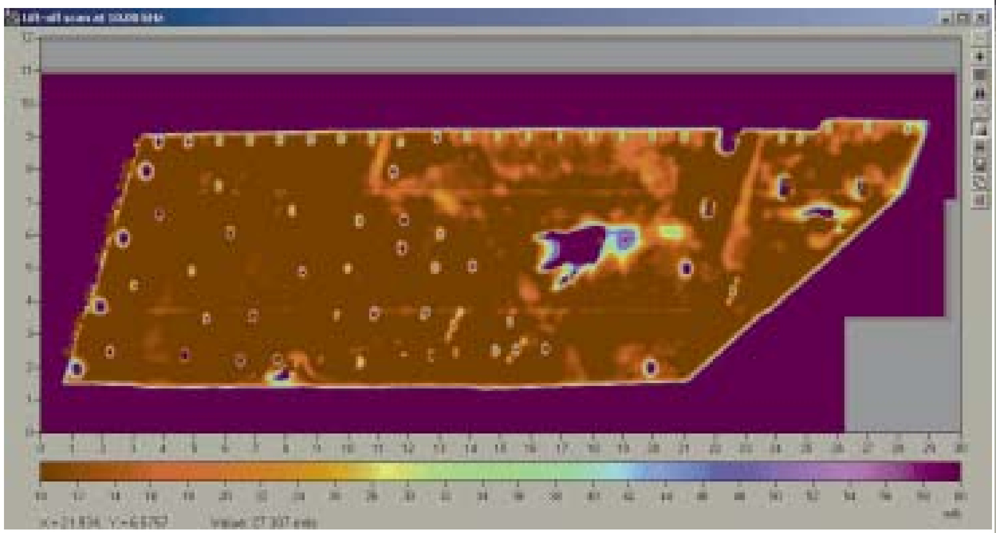


C-130 FLIGHT DECK CHINE PLATE MWM-ARRAY HIDDEN CORROSION IMAGING

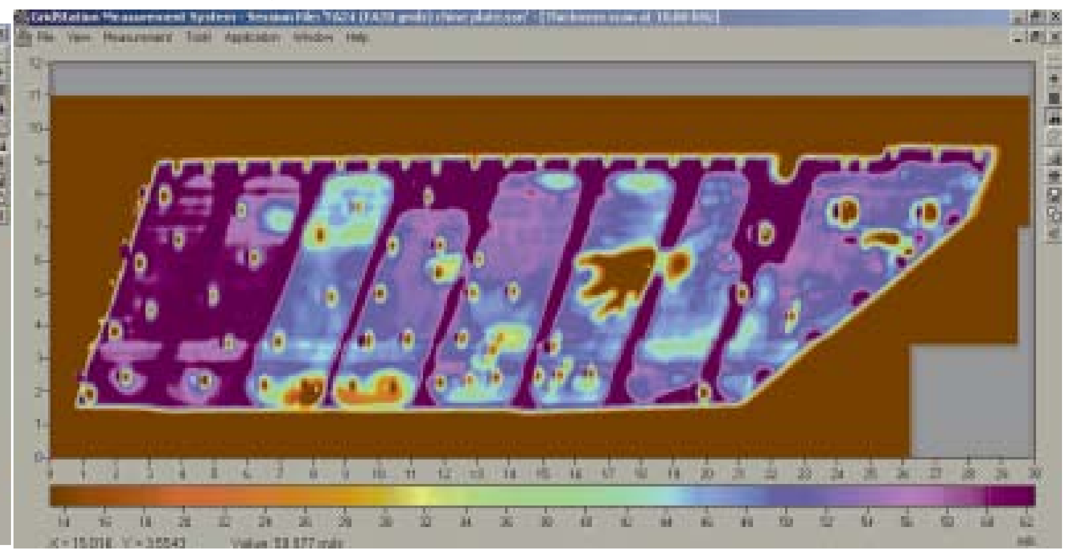
C130 Flight Deck Chine Plate



Surface Topology Image



Thickness Image from Accessible Side



Cost-Effective Identification of Weld Repaired F402 Engine Blades

A recent failure of a weld-repaired F402 compressor blade led to a Cherry Point NADEP decision to inspect the 10,000 blade population to identify blades with weld-repaired tips. Although several inspection options for identification of weld-repaired blades were available, only one technique provided a simple, low-cost answer.

Macroetching would require very aggressive chemicals and was eliminated due to environmental and safety concerns. Radiographic inspection of over 10,000 blades at an estimated cost of $25/blade was judged to be too expensive.

Cherry Point NADEP was already in possession of a JENTEK GridStation inspection system. This system employs a conformable eddy current sensor, called an **MWM** , and was being used by Cherry Point to inspect P-3 propeller blades for a cold work condition. NADEP decided to explore whether the JENTEK system could effectively identify the weld repaired compressor blades.

On Wednesday, 20 December, 2000, Richard Wood of Cherry Point NADEP contacted JENTEK and requested an upgrade of the existing system. Two days later, JENTEK shipped an upgrade of the existing system including a module for inspection of titanium components, a different MWM sensor tip, and a customized inspection procedure. On Tuesday, 26 December, 2000, Mr. Wood called JENTEK to advise that **the procedure works "like a charm."** Figure 1 shows a typical MWM response for a blade with a weld repair. Note that the MWM measured conductivity plotted in Figure 1 is in percent of International Annealed Copper Standard (IACS), where 100%IACS = 5.8×10^7 S/m.

By 28 December, 2000, the first 47 blades were inspected by MWM. Only one blade with a weld-repaired tip had been detected. Etching of all 47 blades confirmed that the blade with the MWM-detected weld repair was the only weld-repaired blade in the set of 47 blades.

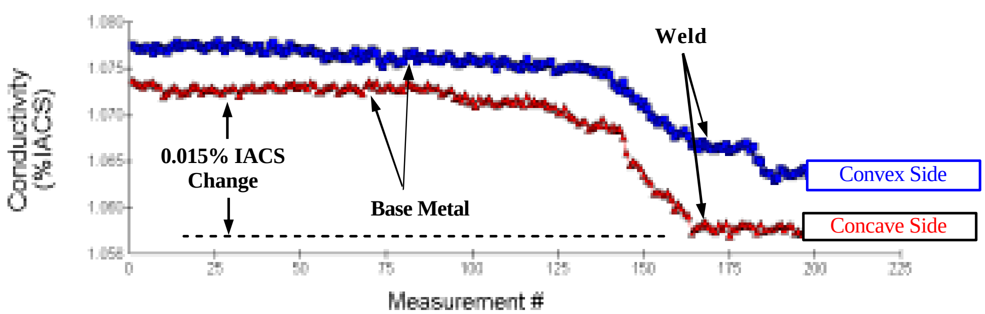


Figure 1.

Subsequently, eight inspectors were trained to perform the MWM inspection. Mr. Wood, who had been previously trained by JENTEK, was able to conduct this training without further assistance from JENTEK. As a part of the training, the inspectors had to inspect a set of 100 blades, including two blades with tips restored by welding. All eight inspectors correctly identified the two blades as weld-repaired with no false detections. Regular MWM inspections of the blades began in February 2001. The typical inspection time has been **less than 1 minute per blade**. To date, over 8,000 blades (over 80 percent of the suspect population) had been inspected. Blades with weld repairs were identified. These blades are slated for radiography to verify the quality of the welds and to determine whether they will be excluded from further use.

Estimated savings from implementation of the MWM procedure for this specific short-term titanium blade weld inspection will be over $200,000, with an incremental cost of approximately $15,000 to the Navy for the software module upgrade, set up and limited performance test by JENTEK, a **ROI of over 5:1**. This estimate accounts not only for the $15,000 but also for the cost of MWM inspections as well as for the cost of radiographic examinations of the much smaller subset of blades. There is also a significant environmental impact of replacing the etching process for this and potentially other applications.

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Aging Systems Office

PRAM FUNDED NDI TECHNIQUE IMPROVES PROCESS FOR INSPECTING C-130 PROPELLER BLADES

Background: H-60 model propeller blades used on C-130 aircraft experience high centripetal and aerodynamic loads. The base of the blade is cold rolled which imposes a compressive preload on the surface making properly cold rolled blades unlikely to initiate cracks. But, in a series of catastrophic failures, a problem was identified in the cold roll process that resulted in several improperly cold rolled blades. The result was the loss of one aircraft and the near loss of several others. After two recalls of 840 propeller blades for suspected cold rolling deficiencies, the OEM has initiated a third recall 13,000 blades. At least half of the blades in this recall belong to the USAF.

Problem: Until recently, the only approved means for inspecting blades for proper cold rolling was to apply a strain gage rosette at the base of the blade and record strain relief as a hole is milled at .001 intervals. The process took four hours, cost $360 per blade and was partially destructive

Success: In 1998, PRAM provided funding to WR-ALC to determine if an NDI process called Meandering Winding Magnetometry (MWM) was capable of detecting improperly cold-rolled propeller blades. The project put a prototype MWM system in a production environment. MWM has demonstrated the capability to detect properly cold rolled blades as confirmed by blind hole drilling. Inspection time has been reduced to 20 minutes and the project has generated a 32:1 return on investment. Due to the success of this PRAM project, other applications of MWM are being considered. OC-ALC has submitted a project which would use MWM to inspect the high pressure turbine disc on the F110 engine and WR-ALC has asked us to fund a project that would use MWM to inspect 25mm gun barrels.

Remote Instrument Module

MWM Probe

Propeller Inspection Region

Additional Information

To receive more information about Meandering Winding Magnetometry or any other project the Aging Systems Office is funding, contact us at 937-255-7210 or at DSN 785-7210. You can also visit our web site at http://www.wpafb.af.mil/asc/sma to find out how we might be able to fund your idea.